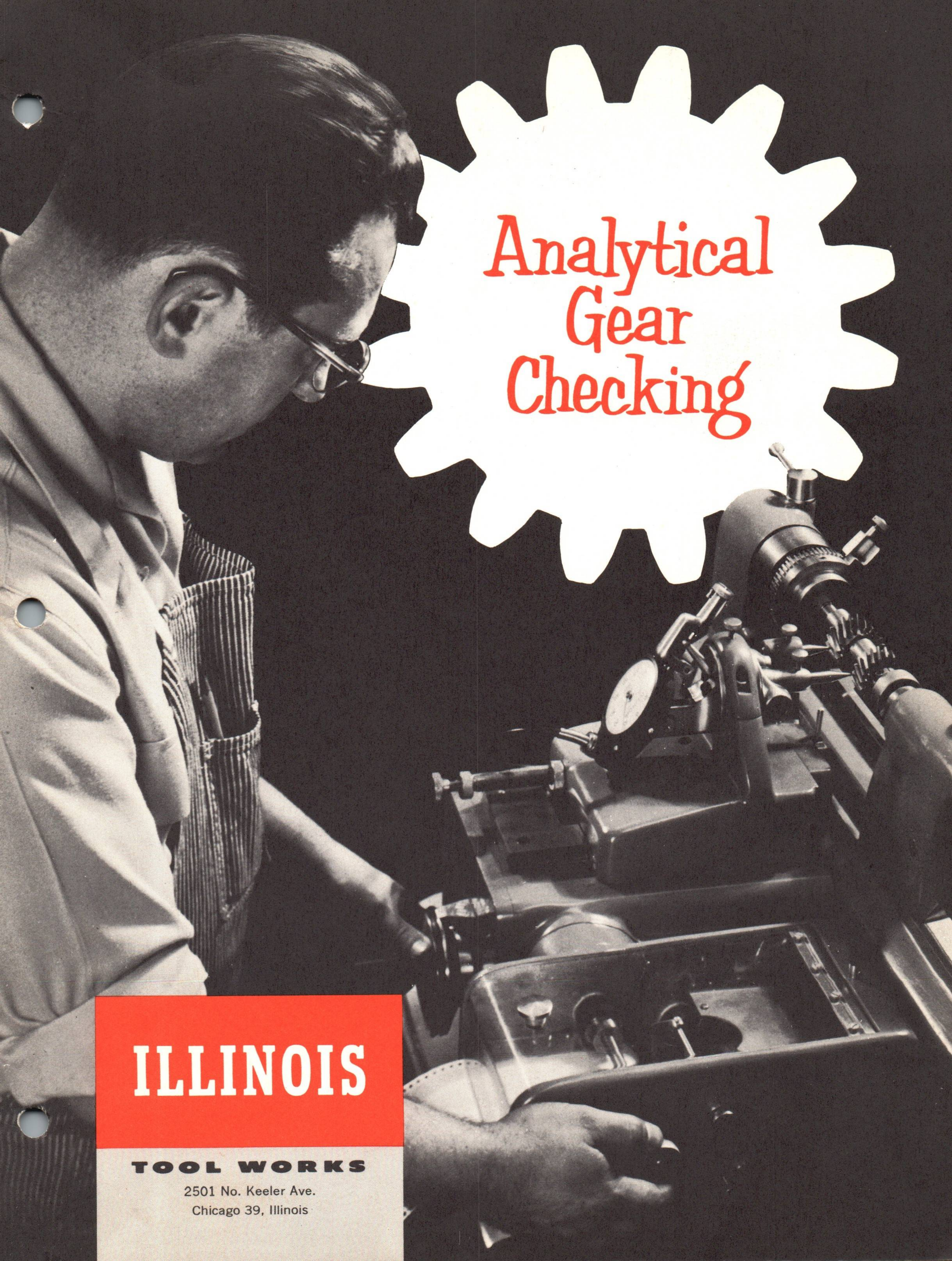
Analytical Gear Checking



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Chicago 39, Illinois

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Analytical Gear Checking

ILLINOIS TOOL WORKS
TOOL & MACHINE DIVISION
CHICAGO, ILLINOIS

The universal aim in the production of gears for any application is a definite degree of uniformity. To control and assure this uniformity is the purpose of gear inspection. Aircraft gears designed for high load carrying capacity provide an excellent example. Their degree of uniformity is exceptionally high. In the automobile industry, manufacturers are very sensitive to noise in their gears even in the low-load condition when a car rolls slowly along a level road. Again, uniformity is vital. Machine tool indexing gears must have exceptionally accurate tooth spacing, another problem of uniformity.

In these instances gear inspection is essential to assure maximum load carrying capacity, minimum noise, maximum indexing accuracy, or any combination of these service requirements.

Even in the case of gears that do not have to meet the extreme service requirements of aircraft, automotive and indexing gears, the dynamic loads imposed upon gear teeth as a result of the usual manufacturing errors can easily double the rated tooth loading, even in a well proportioned gear. *Most gears could easily be reduced in size if manufacturing could produce them more accurately.*

Some think of the gear inspection as a costly evil, to be applied only to the most accurate gears. The real problem, however, is only in finding the proper *type* and *degree* of inspection because gear inspection, correctly applied, actually *reduces overall costs.* The right kind of gear inspection is meant to hold manufacturing expenses to a minimum by:

1. Assuring a definite degree of uniformity in keeping with the specific service requirements;
2. Permitting engineers to specify the most economical gear size and design;
3. Reducing scrap and rejections.

Gear inspection today means control over an increasingly complicated manufacturing cycle where hobbing depends upon blanks, shaving upon hobbing and final accuracy upon heat-treatment in addition to all other previous operations.

The determination of the most economical checking procedure is a relatively complex thing. It is influenced by the size of the manufacturing department, the nature of its production runs, the type of gear produced and the skill and knowledge of its people. Fortunately, the variety of checking procedures is as wide as the variety of gears. The purpose of this article is to describe various procedures and explain the advantages and application.

If it were the aim to produce as good a gear as possible on a hobbing or shaping machine, the first thing to do would be to *obtain an accurate tool.* In hobbing the amount of involute error is determined by the hob. Hobs are divided into four classes and it is particularly the amount of lead variation per revolution, commonly called the "weave", which distinguishes one class from the other. This lead variation is duplicated in the involutes of gear teeth, possibly further aggravated by slight amounts of shape error, sharpening error and runout after mounting. With proper care in mounting and sharpening, however, the inherent weave error of a hob is the biggest contributor to involute inaccuracy. For a 10 D.P. gear, the allowable "weave" of an "A" tolerance hob is .0005. Allowing for some additional error, it would be safe to predict that the involute errors in the gear will be limited to .001.

In the case of Illinois Tool Works hobs, the effect of the generating tools on the finished gears can be accurately predicted by means of the Toolgraph Chart (Figure 1) which accompanies every hob shipped. This chart is an electrically produced graph of final inspection results and shows those hob characteristics which affect gear accuracy quite clearly.

The situation will be somewhat different if gears are shaped. The involutes of shaper cutters are held to very close tolerances. In the above case of a 10 D.P. gear, the tolerance would be .0002. Additional errors as a result of stress and deflections during cutting would permit the prediction that the involute errors in the gear will be within .0005. Therefore, in either shaping or hobbing, involute accuracy is predictable by the choice of the tool and the care in mounting and maintaining it.

While such a statement may be made about the shapes of gear teeth, it cannot be made about their spacing. Yet, spacing is just as important as the involute form in determining the smoothness of engagement of a pair of gears. The spacing of gear teeth is entirely a function of the machine in the case of hobbing and the combined function of the cutter and machine in shaping. Spacing is only controllable through the generating machines and, while these machines were probably accurate originally, wear or abuse may have altered the situation. Therefore, indexing accuracy should be measured periodically.

Since spacing is almost exclusively determined by the indexing worm and gear of the hobbing machine, and by the combination of the work and cutter spindle of a shaping machine, it is entirely safe to assume that if these machines produced good spacing in a 36 tooth gear, they will also produce good gears of other numbers of teeth. Therefore, there is nothing to prevent an operator of a hobbing or shaping machine from cutting a 36 tooth sample gear and having it inspected by someone with index checking equipment. Care must be taken to be sure that the sample gear blank is well made, because location at the time of hobbing must be duplicated in checking or errors occur for which the machines are not responsible.

Since this check should be repeated from time to time, a good investment in checking equipment is a 36-tooth index plate, used as shown in Figure 2.

Illinois Tool Works index plates of 10″ diameter are made to an accuracy of .0003 total index error, only 12 seconds of arc, a small fraction of the indexing error found in most generating equipment.

Another method for the same sort of check is shown in Figure 3. The reliability of such a

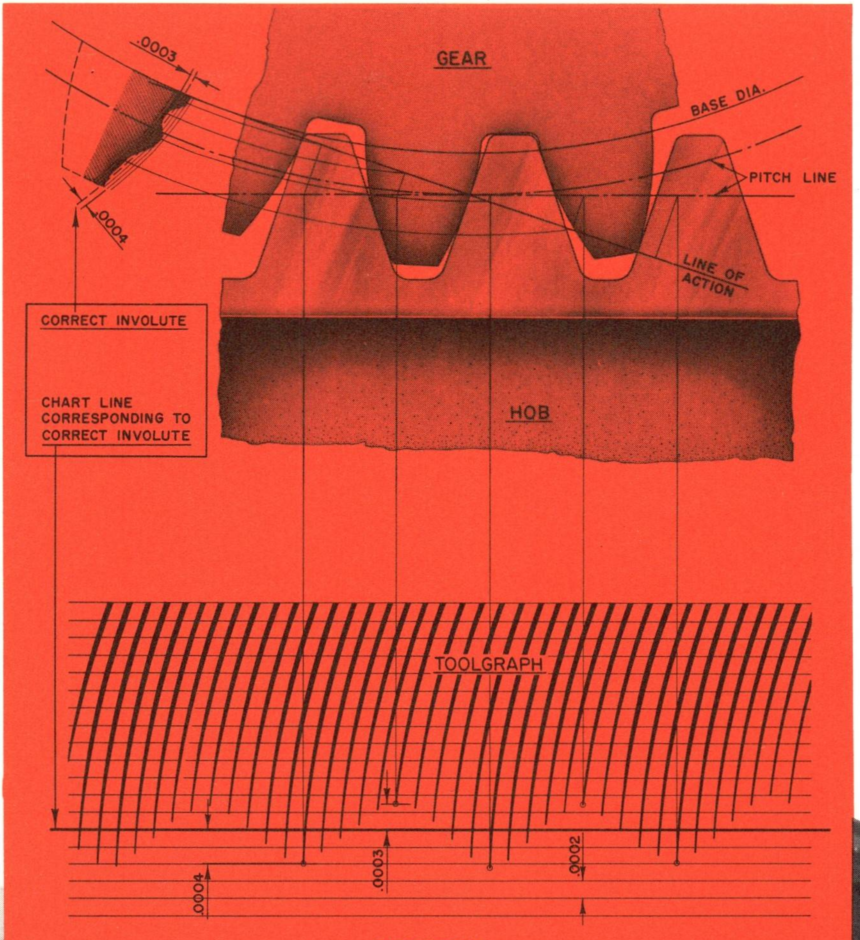
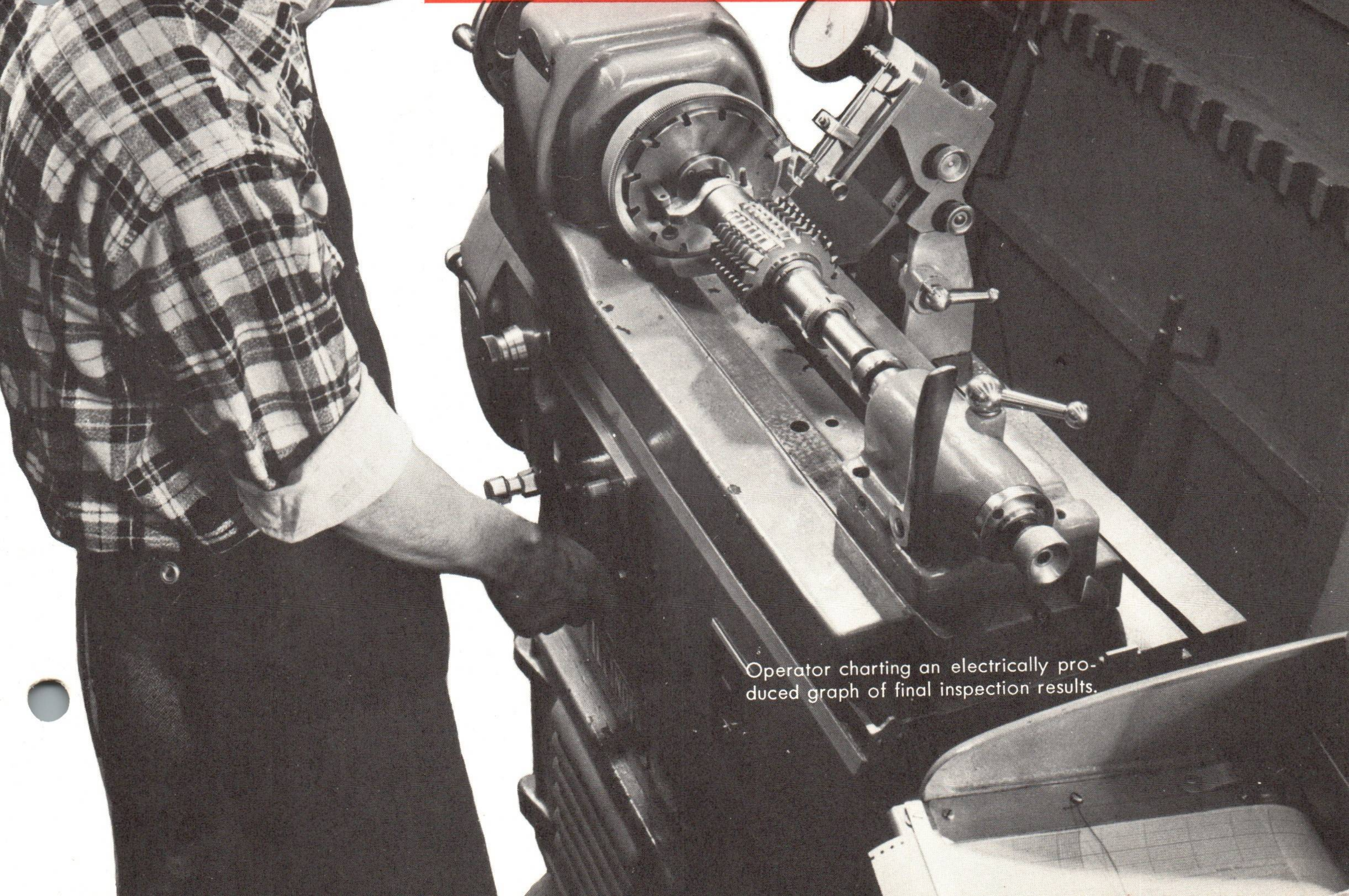


FIGURE 1



Operator charting an electrically produced graph of final inspection results.

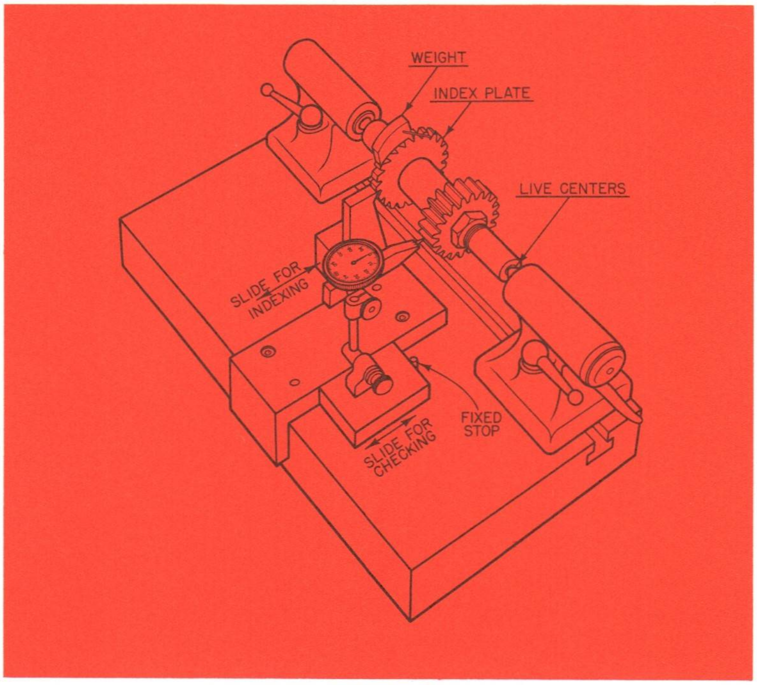


FIGURE 2

Tooth space checking with an Illinois Tool Works index plate.

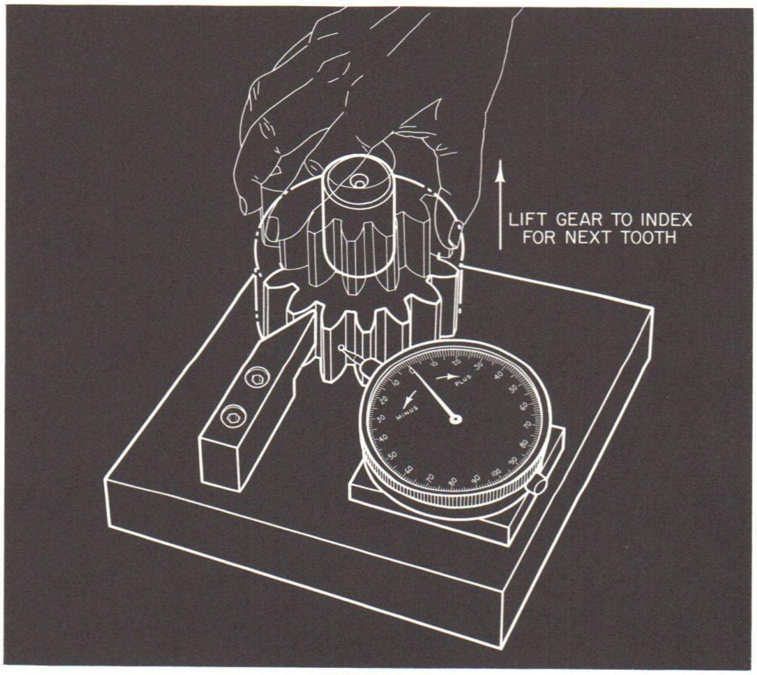


FIGURE 3

Space comparison check without index plate.

space-comparison check is only limited by the sensitivity of the equipment and the skill of the operator.

Modern gear generating equipment is never expected to produce a radical spacing error between adjacent teeth. Their greatest indexing error is in small but persistent accumulations.

Therefore, it is frequently argued that the space comparison test cannot be used to arrive at the so-called "accumulated error" It is true that the spacing error between adjacent teeth on a generated gear is of the magnitude of .0001 to .0005 and it is admitted that failure to interpret the dial indicator readings could lead to wrong accumulated values. But experience shows that the slight misinterpretations of the dial indicator readings are as often in the minus direction as they are in the plus direction and that the two cancel each other out when quite a few teeth are checked.

Even if the space comparison test is rated somewhat inferior to the optical dividing-head or index plate-check because of the dial indicator (400 to 1 magnification) and dependence upon operator skill, it is still a very useful tool. Its main trouble is that using it to arrive at the accumulated spacing error involves a bit of work. This is what must be done: In the interest of brevity, assume that the tooth comparison check was performed on a 12 tooth gear. The following readings were marked down:

TABLE 1

Tooth Number	1	2	3	4	5	6	7	8	9	10	11	12
TT Indicator Reading	0	+.0002	+.0003	+.0004	+.0002	0	0	+.0001	–.0002	–.0001	–.0002	–.0001

Since the gear has a full number of teeth, any spacings which are too large must be offset by others which are too small. The sum of all readings in the check adds up to +.0006 which indicates that the operator was wrong in setting the dial indicator to "zero" at the initial space. He must make a correction of –.00005 for each reading and revise the check like this:

TABLE 2

Tooth Number	1	2	3	4	5	6
Corrected Indicator Reading	–.00005	+.00015	+.00025	+.00035	+.00015	–.00005
Tooth Number	7	8	9	10	11	12
Corrected Indicator Reading	–.00005	+.00005	–.00025	–.00015	–.00025	–.00015

With this little arithmetical correction, all plus spacings equal all the minus ones, which is as it should be. The operator would arrive at the same figures if he repeated the check, setting the dial indicator at –.00005 at the start. From here on it is very easy to arrive at the true out-of-position or accumulated error of any tooth by progressive addition.

TABLE 3

Tooth Number		1	2	3	4	5	6
Algebraic Addition	0	–.00005	+.00010	+.00035	+.00070	+.00085	+.00080
Tooth Number		7	8	9	10	11	12
Algebraic Addition		+.00075	+.00080	+.00055	+.00040	+.00015	0

This addition may be clarified by making the graphic chart from Table 2 shown in Figure 4.

It is now clear that the out-of-position errors range from +.00085 to −.00005, a total of .0009. If the gear were 4″ P.D. or 2″ pitch radius, the total error at a 1″ radius would be .00045 or 11 seconds over 150°.

The important point is; if the gear is an indexing gear, is this error tolerable? If it is a power transmitting gear, can its performance, wear, and noise characteristics be improved by replacing the machine indexing gears?

Gear generating machines must do more than space gear and spline teeth correctly. If the gears are spur gears, their teeth should be parallel to their axis. If helical, their lead should be correct. A check for parallelism needs no further explanation. To check up on the machine's inherent ability to produce a correct lead, it might be deliberately set to produce a 64″ lead. A sample gear could then be cut using the same cautions as previously mentioned for the sample which was checked for spacing. Such a sample helical gear might be inspected by someone who is equipped with a lead checking machine, but again, as in the case of space checking, a lead gage may be obtained and a comparison test made as shown in Figure 5.

Lead gages made by Illinois Tool Works come with a variety of four leads. One of the leads is infinite and therefore can be used for checking spur gears in the arrangements shown in Figure 5.

Up to this point, inspection has not been carried to the gears as such. It has consisted of a periodic check to verify the basic, inherent accuracy of the machines. A certain degree of control over involute errors was admittedly possible through the proper selection of the type and class of tool.

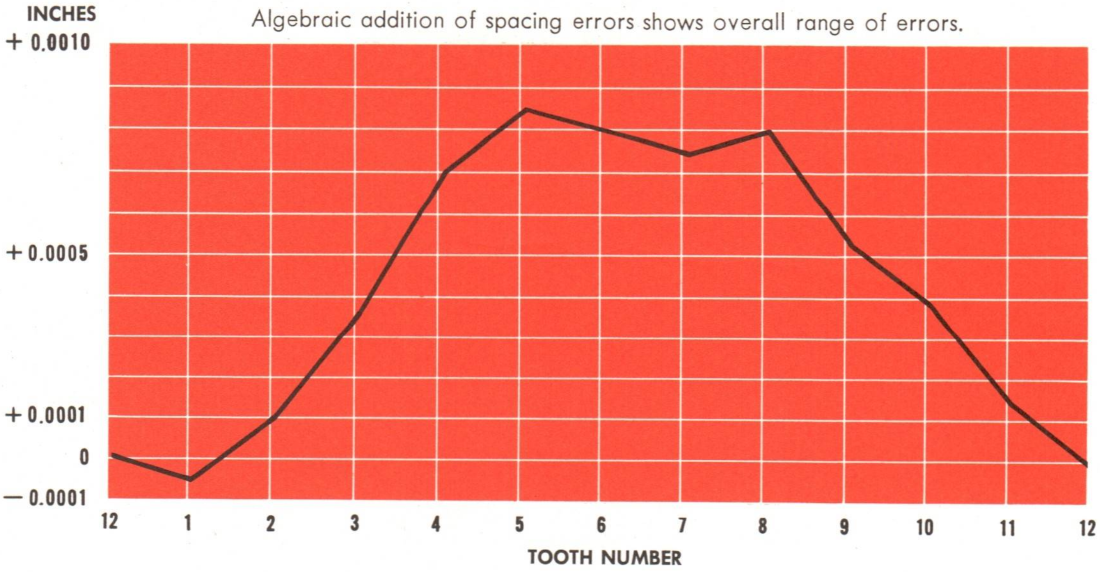
In theory it might be possible to control the quality of gears by consistently checking parts of the machine, tools, gear blanks and arbors, everything capable of causing errors. But it would be a hopeless task, complicated by the fact that a lot of errors are additive. It would be necessary to maintain exceedingly close tolerances everywhere in order to keep their possible additions within limits.

To put it differently: if the accuracy of a gear is such that obtaining it requires true running, precisely sharpened hobs and true running work arbors, then the gears themselves require checking. It is far more economical to check the gears and trace any excessive errors back to their source.

Basically, there are two distinct types of gear checking, functional and analytical. The first consists of testing gears by the way they roll or function. The second comprises the various methods which check the dimensional characteristics of a gear such as involute, lead, or spacing.

FIGURE 4

Algebraic addition of spacing errors shows overall range of errors.



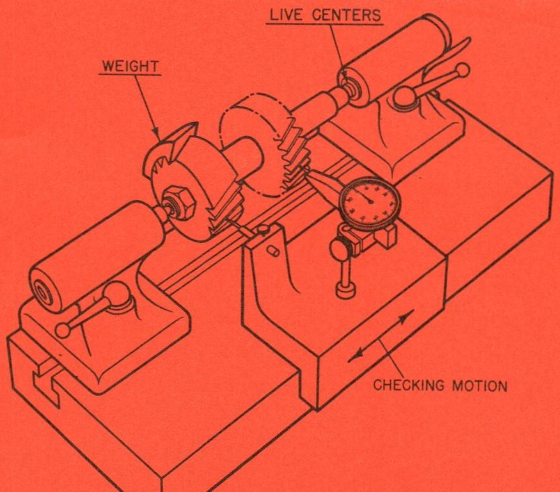
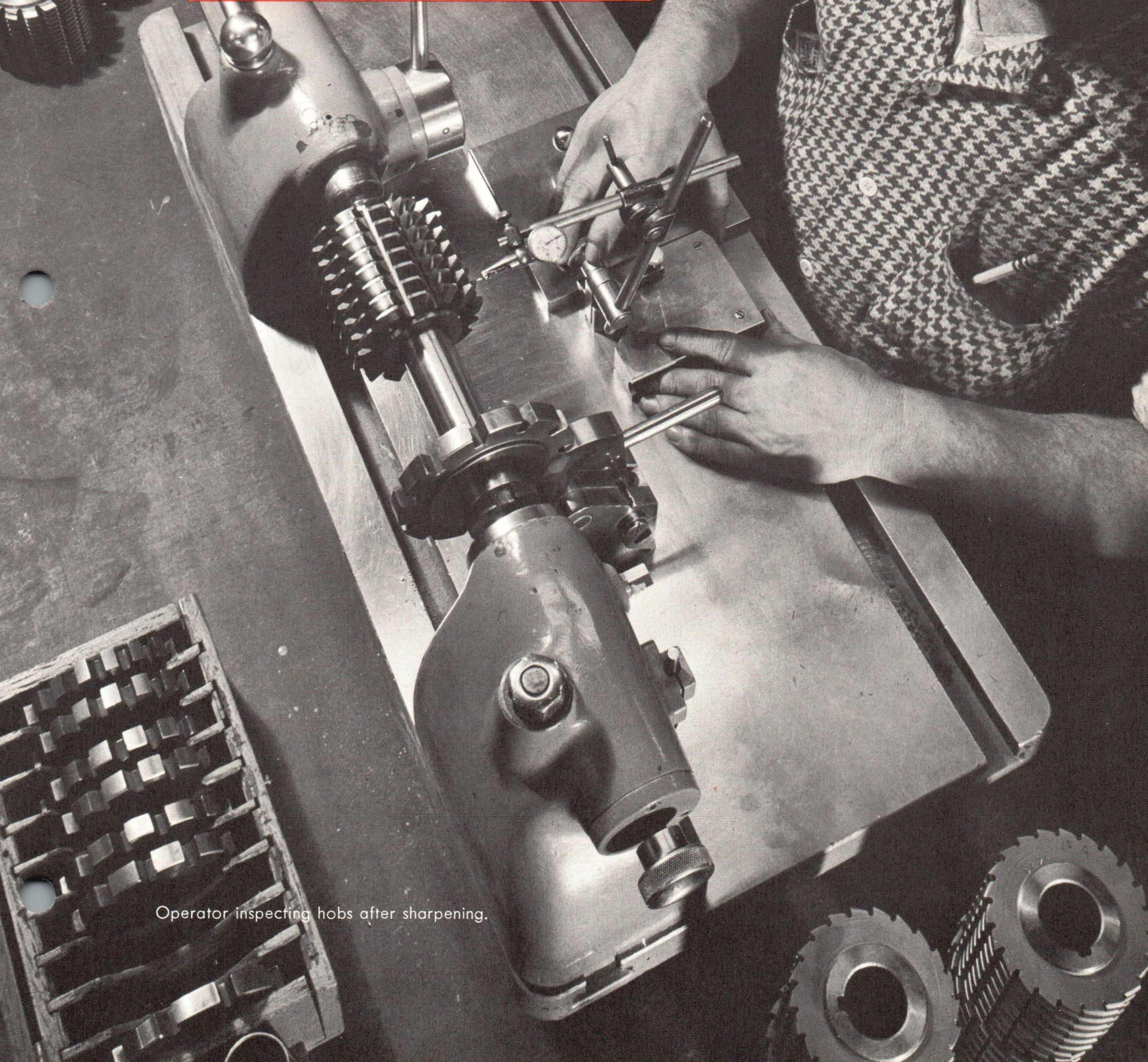


FIGURE 5

Checking lead of a helical gear with an Illinois Tool Works lead gage.



Operator inspecting hobs after sharpening.

For most gears, the main criterion of quality is smooth rotation even when idling. Since that can only be achieved by relatively true running gears, with good involutes and spacings, it is certainly justifiable to check the smoothness of rotation without always going into all the details of runout, spacing and involute. This means checking a gear by the way it functions.

In the history of the development of modern gear checking, testing gears by the way they roll or function came first. Today, in the most up-to-date gear departments, gear rolling fixtures, using master gears and indicators are placed directly alongside the hobbing, shaping, and shaving machines to constantly check the output of these machines. They are also placed in the Final Inspection Department—sometimes combined with recording. As more elaborate universal machines, usually combined with recording, they are an important part of every gear laboratory.

Functional gear checking gives a true measurement of size and runout. Beyond that, it gives an admittedly distorted, but nevertheless indicative, picture of the individual tooth errors. Of course, gear rolling cannot reveal form errors on gears which are heavily modified for deflection under load, nor will it serve to check the intentional lead variations (crowning) which compensate for mismounting. In the case of these gears, gear rolling is used solely to measure size and runout and detect nicks or burrs.

In the broad and general field of gear production, the functional gear checking machines are the *policemen* of the process. Analytical checking machines for inspecting involute, lead and spacing are the *judges*.

Because of the importance of the rolling check, Illinois Tool Works has devoted a special pamphlet to this particular phase of gear checking called *Functional Gear Checking*. The basic gaging element in gear rolling is, of course, the master gear. Aside from the limitations inherent in any composite check, gear rolling is no more reliable than the master gear. Inaccuracies in a master gear can be very costly in production because errors in the master contribute to the indicator movement and thus leave a smaller tolerance for the production process. They keep operators from getting identical results on successive checks. In the way these master gear errors increase or cancel those in the production gears, they may cause a good gear to be rejected or a bad one to be accepted. Great accuracy is therefore the most important characteristic of master gears. (See Illinois Tool Works pamphlet *Know Your Master Gears.*)

All errors indicated in gear rolling are *composite* errors. If the check is recorded, the graph looks similar to Figure 6. The individual tooth errors represent a composite of from two to four gear flanks in simultaneous contact. These individual tooth errors in turn are arranged on a coarser wave pattern which represents the runout or, more generally, the out-of-roundness of a gear. The so-called "total composite error"—which is usually the error looked for in gear rolling—is therefore again a combination of the runout and the composite tooth to tooth errors.

As a rule, the runout error is much larger than the individual tooth errors. Therefore, if limits are assigned to the rolling check, they will be influenced by the decision on the permissible amount of runout. Standardized tolerances for total composite error are not yet available, however, the A.G.M.A. lists the values for runout shown in Table 4.

The runout tolerances in Table 4 were suggested by the A.G.M.A. Additional charts for other gear errors will appear on other pages of this pamphlet. These tolerances are grouped according to pitch, pitch diameter, and speed range. There are, however, many gears for which the speed range is of no particular significance. For those, it should be borne in mind that the tolerances reflect not merely the requirements for each speed range, but also the capability of the various manufacturing processes. Therefore, Class 3 or 4 tolerances might be applied to accurate index or change gears even though their rotational speed would place them in Class 2. Gears serve so many purposes and such a variety of requirements that it is impossible to establish any system of tolerances covering all contingencies. However, a thorough un-

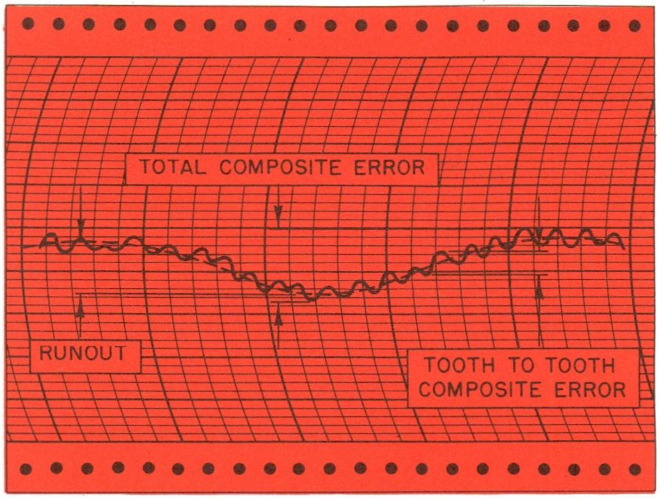
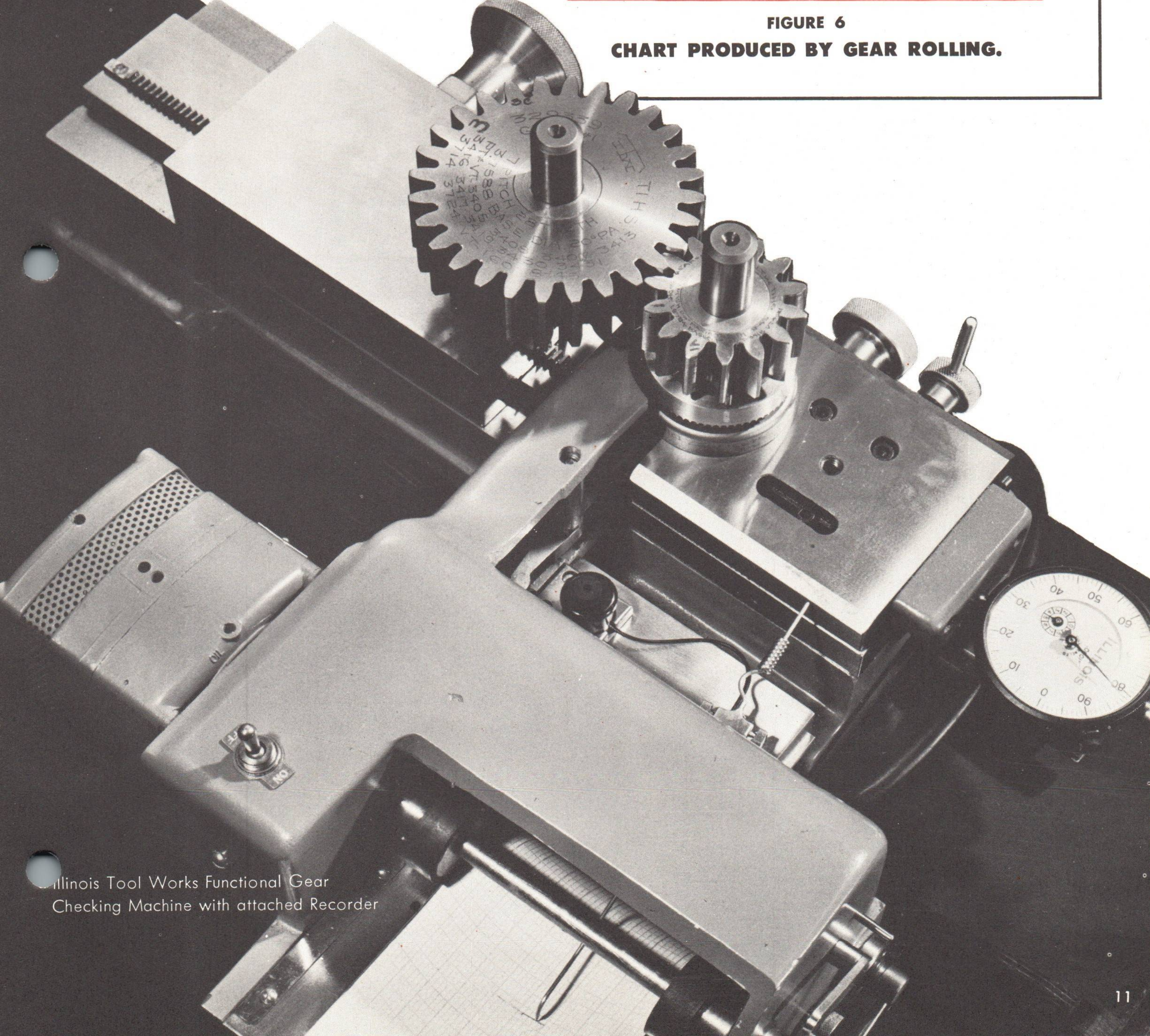


FIGURE 6
CHART PRODUCED BY GEAR ROLLING.



Illinois Tool Works Functional Gear Checking Machine with attached Recorder

TABLE 4

Class	Diametral Pitch	*Runout Measured on Pitch Circle Total Indicator Reading								
Pitch Diameter, In.		**¾**	**1½**	**3**	**6**	**12**	**25**	**50**	**100**	**200**
Class 1 (Up to 80 fpm)	½	. . .	. . .	. . .	. . .	. . .	100	100	140	180
	1	. . .	. . .	. . .	. . .	70	90	90	100	150
	2	. . .	. . .	. . .	60	60	80	80	90	120
	4	. . .	. . .	50	60	60	80	80	90	120
	8	. . .	30	50	60	60	80	80	. . .	. . .
	16	30	30	50	60	60	80	. . .	. . .	. . .
Class 2 (Up to 400 fpm)	1	. . .	. . .	. . .	. . .	30	35	40	45	60
	2	. . .	. . .	. . .	20	20	25	30	35	45
	4	. . .	. . .	20	20	20	25	30	35	40
	8	. . .	15	15	20	20	25	30	. . .	. . .
	16	15	15	15	20	20	25	30	. . .	. . .
Class 3 (Up to 2000 fpm)	2	. . .	. . .	. . .	20	20	25	25	30	35
	4	. . .	. . .	10	20	20	25	25	30	35
	8	. . .	10	10	15	20	25	25	30	35
	16	10	10	10	15	20	25	25	. . .	. . .
Class 4 (Over 2000 fpm)	2	. . .	. . .	. . .	10	10	12	14	16	. . .
	4	. . .	. . .	. . .	10	10	12	14	16	18
	8	. . .	. . .	10	10	10	12	14	16	18
	16	. . .	10	10	10	10	12	14	16	. .

**All tolerances in ten-thousandths of an inch.*

Until such time that standard tolerances are available, the runout figures, with a percentage, say 20% added to reflect individual tooth errors, could be used as a guide for total composite error.

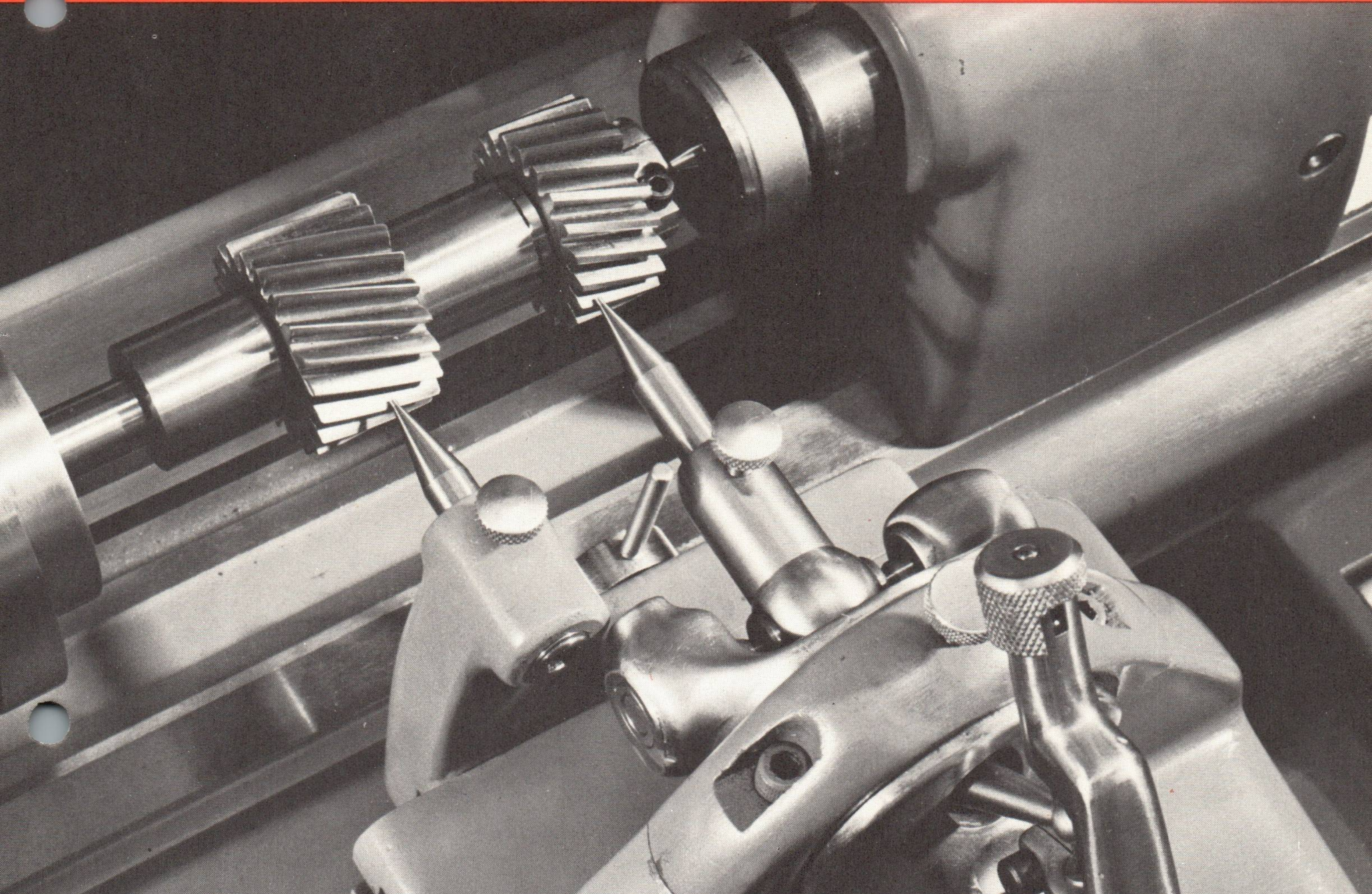
derstanding of the nature of gear errors and the intelligent application of tolerances will extend the usefulness of these tolerances beyond the immediate limitations of the charts.

The inherent limitations of gear rolling are apparent from the previous description of what it is. To repeat: it is a *composite* check which reflects the combined errors of two to four gear flanks in action at a time. If excessive errors were shown on the indicator or chart, it is impossible to know whether the right-hand or left-hand profiles were at fault and whether the involutes or the spacing were off. It was also previously pointed out that lead errors are not revealed at all and the same applies for any intentional modification in either lead or involute. Those questions will have to be settled by subsequent involute, lead and space checking.

It appears then, that the next step in the control of gear accuracy would require a series of analytical machines for involute, space and lead checking. While this step is readily taken by those people whose production easily justifies the investment, it is a painful step for most others because of the high cost of these machines. Manufacturers of involute, space and lead checking machines must spend a great deal of time and effort to make their equipment go through the intricacies of a lead or involute movement so precisely that the machines themselves take but a small portion of the allowable gear errors. Since involute and lead tolerances for some gears can be as close as .0002, that does not leave much for these machines.

Actually, the high investment as well as the bulk of analytical gear checking equipment, limits even the large gear producer who has a seemingly well equipped laboratory. As a rule, he does not have enough equipment for the effective control of his process and, just as frequently, the laboratory is too far away from the scene of production.

However, there is a valuable intermediate step between the simple gear rolling fixture and the more intricate analytical involute, space and helical lead machines. That is the Analytical Comparator shown in Figure 7. On this machine the use of a master gear specifically designed for the purpose is recommended, but if a rolling master is made with the same number of teeth as the product gear it may be used



Illinois Tool Works "Analytical Comparator" provides lead, involute and space checks in one machine.

FIGURE 7

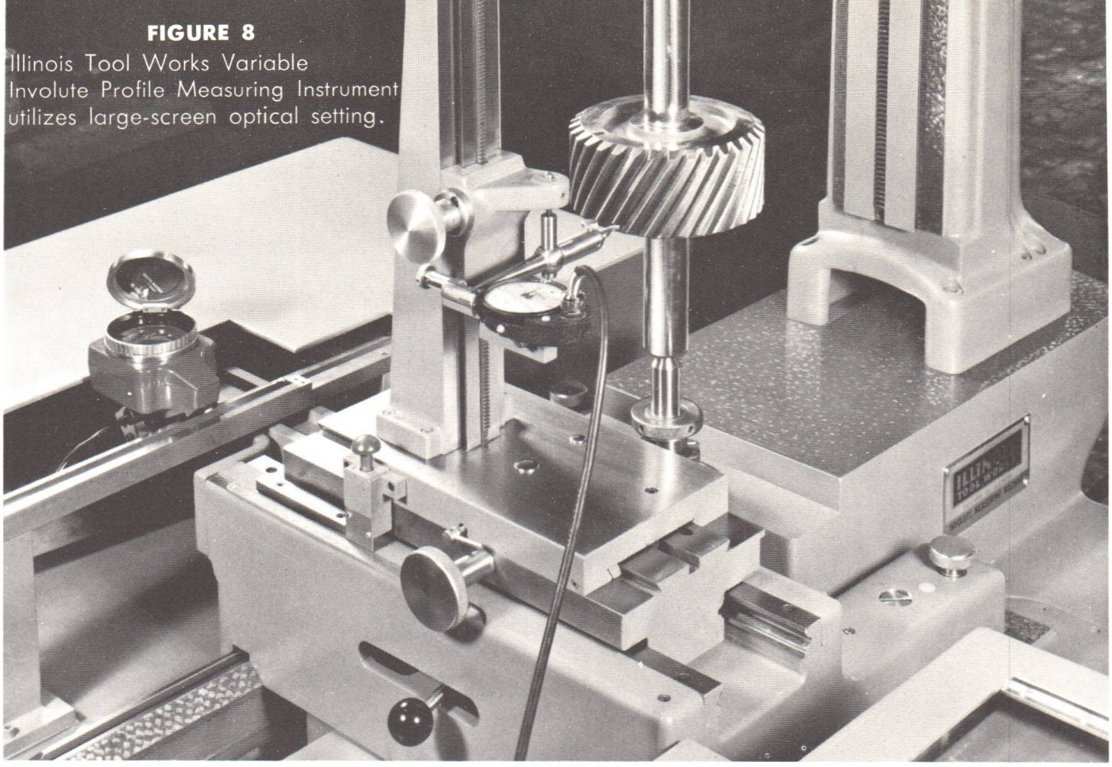


FIGURE 8
Illinois Tool Works Variable Involute Profile Measuring Instrument utilizes large-screen optical setting.

on the Analytical Comparator for checking involute, spacing and lead of a spur-gear. However, only involute and spacing of a helical gear since, as a rolling master, it would have the opposite hand of helix.

The novelty of the machine in Figure 7 lies in the combination of all checks. The table motion parallel to the axis compares lead. The perpendicular motion checks involute or tooth profile and the in-and-out motion of the indicator slide checks the spacing. This type of check, of course, is only as accurate as the master gear. On the other hand, it *is* as accurate as the master gear because the machine motion as such, other than the indicator and recording system, have no effect upon the results—and modern recording systems are every bit as precise, if not more so, than dial indicators.

Table 5 gives the tolerances which are commonly held on rolling masters. Those, however, who would like to see even closer tolerances can have special ones made for the analytical check only. In that case, it becomes possible to take advantage of the fact that the masters need not necessarily have a full compliment of finished teeth as the gear. Grinding fewer teeth facilitates higher accuracy. Such a master may have one-half, one-third or one-fourth the number of teeth of the gear. That eliminates, of course, the tooth to tooth check and its place

TABLE 5

GRADE "A" GROUND SPUR MASTER GEAR TOLERANCES *(Coarse Pitch Series)*

DIAMETRAL PITCH		4-5.999	6-11.999	12-19.999
ACTIVE INVOLUTE PROFILE (TOTAL INDICATOR VARIATION)		.0003	.0002	.0002
MEASUREMENT OVER PINS	13° TO 19° P.A.	±.0014	±.0011	±.0007
	OVER 19° P.A.	±.0010	±.0008	±.0005
PITCH DIAMETER		**4.250" or Less**	**4.251" to 6.250"**	**6.251" to 8.250"**
RUNOUT (tiv.) AT APPROX. P.D.	13° TO 19° P.A.	.0007	.0008	.0009
	OVER 19° P.A.	.0005	.0006	.0007
SPACING (MAX. VARIATION BETWEEN ADJ. TEETH)		.0002	.0002	.0003

Lead or Parallelism . . . max. of .0001 deviation in central 80% of face width. .0001 additional allowed adjacent to each face.

Face Runout (tiv) . . . . .0001" per inch of diameter

Grade "B" tolerances—same as above except ±.005 over pins

Hole Size . . . . $\left\{\begin{array}{l}+.0002'' \\ -.0000''\end{array}\right.$

Outside Diameter . . . . ±.0010"

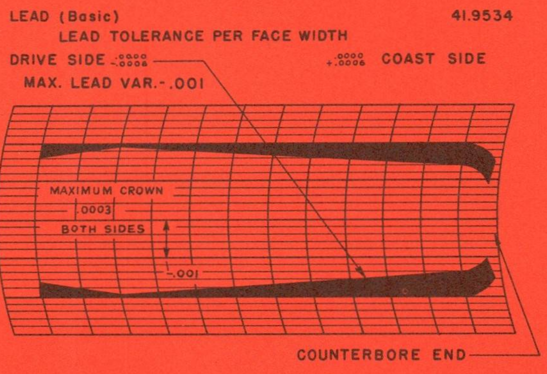
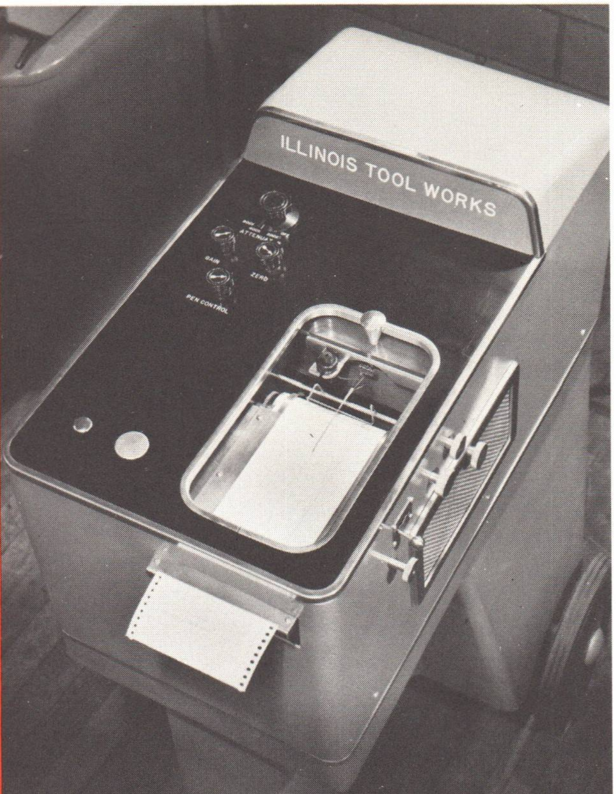
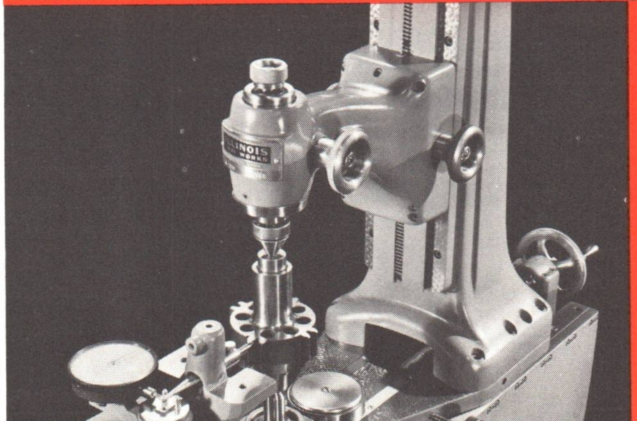


FIGURE 9

Courtesy Detroit Transmission Division
General Motors Corporation



Illinois Tool Works Electrical Recorder.



Illinois Tool Works Involute Measuring Machine.

FIGURE 10

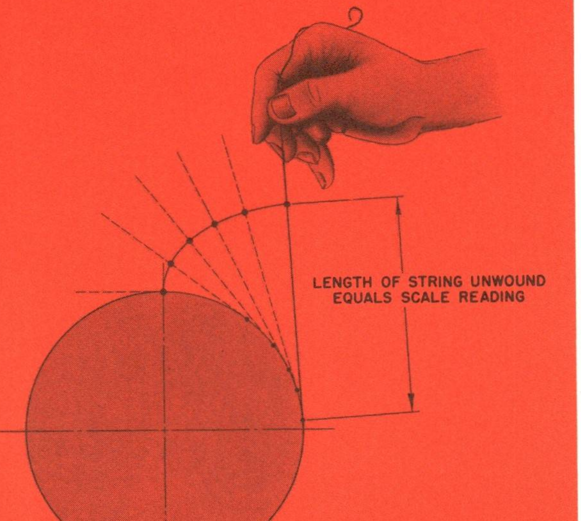


FIGURE 11

is taken by a space comparison over two, three, or four teeth as the case may be. Spacing as a rule is a relatively stable function of the machine, and needs checking only from time to time. Therefore reducing number of teeth in the master gear is a good compromise in favor of higher accuracy of those components which require constant control.

The analytical comparator is equipped with recording as shown in Figure 8. Recording is almost a necessary addition to all gear checks. The real value of recording lies in the fact that a chart reveals the true condition of the inspected surface much more indicatively than figures can. A recorded graph will reveal, by the nature of its pattern, the cause of the errors whereas, figures representing indicator readings can only tell the magnitude of these errors. Recording is an essential tool in the control of gear accuracy because it indicates where and what adjustments have to be made to improve accuracy.

Recording today is more essential than ever. Many limits have become so close that reliable clues are needed to tell constantly where errors come from. The importance of the graph as a picture which provides clues to the nature and cause of gear errors, far outweighs all other advantages. However, recording may also be a time-saver. It provides a permanent, easy-to-read record which minimizes the chance of human error.

Some highly refined gears cannot be inspected at all without the help of recording. These are the gears on which the tolerances are very close, and the pattern is fixed. Therefore, the working tolerances, rather than being expressed in figures, are shown as an area. Such a tolerance area may be etched on a piece of clear plastic and superimposed upon the graph to see if the actual lead or the involutes are within the tolerance area. See Figure 9. A similar pattern may be visualized for the involutes.

Such patterns anticipate deflections under load, mismounting and deformations in heat-treatment. They usually follow the principle of "crowning" by placing the initial bearing at the best location. The maximum amount of error is thus placed where it will do the least harm. While this system requires more control and inspection, it also permits the greatest possible tolerances with the least damage.

Checking machines which are built specifically for analyzing involutes, lead, or spacing are not only the most accurate tools for the job, but as a rule, have additional features which permit a greater insight into the nature of gear errors which cannot be incorporated into a comparator of the type shown in Figure 7. They are universal machines in the sense that they can be set up to check any gear within their range in a short time. Thus, they are the backbone of all gear laboratories.

Figure 10 shows the Illinois Tool Works Involute Checker. For maximum accuracy, it is a base circle type machine.

Classically, the involute, is described as the curve traced by a point on a taut string unwinding from a circle. This circle is called the base circle. (See Figure 11) Every involute gear has one, and only one, base circle from which all involute surfaces of the teeth are generated. This base circle is not a physical part of the gear. To the engineers it serves as a means of defining the tooth profiles and in the Illinois Tool Works machines it serves as a means for checking them.

As previously pointed out, modern gear control does not merely specify tolerances. It is equally concerned with placing the maximum tolerance where it will do the least amount of harm. In the involute checker shown in Figure 10, the position of an error or intentional modification is given by the scale reading which shows how much the apron has moved from the starting point. The significance of the scale reading as related to the gear teeth is shown in Figure 12.

The scale readings are very useful in the measurement of the involutes because the point of contact between two gear teeth rolling together proceeds along the line of action the same way the contact finger of the machine proceeds along the scale. (For more complete discussion of the line of action picture in the rolling of involute gears, see *The Design of Gear Teeth.*) Therefore, equal scale increments represent equal time incre-

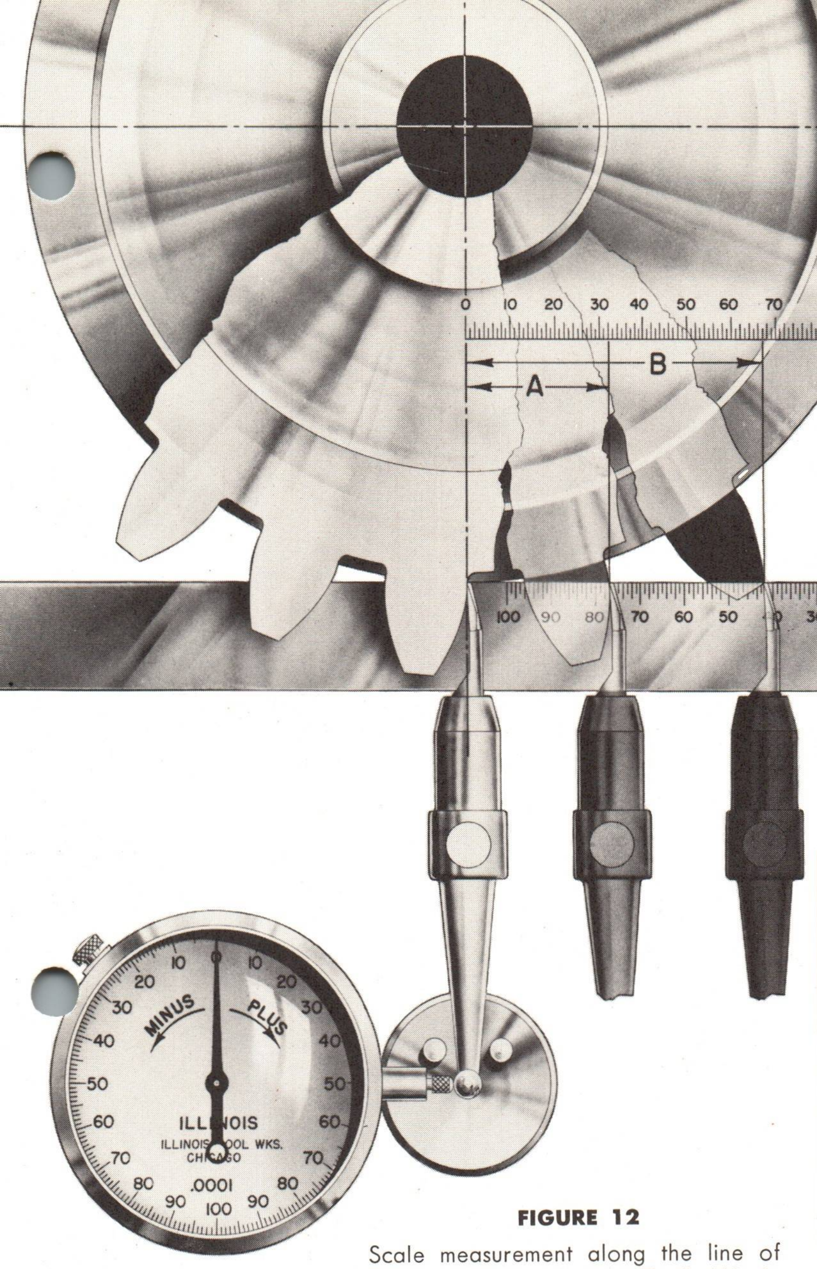


FIGURE 12

Scale measurement along the line of action on an Illinois Tool Works Involute Measuring Machine.

Involute Charts of Mating Gears Superimposed.

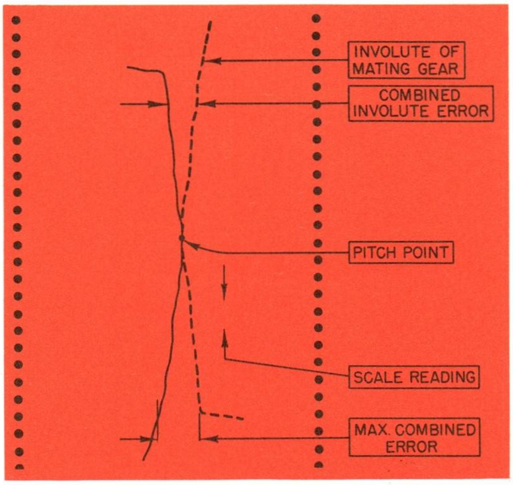


FIGURE 13

ments in the rolling of the gears, and profile charts of mating gears can be compared directly. See Figure 13. Accelerations or decelerations of the mating gears due to involute errors, occur at the same rate as the total errors do when plotted against the scale readings.

The scale reading is also important in its relation to base pitch, or the distance between teeth measured along the base circle. The total range of scale readings on the active profile must be somewhat greater than the base pitch to insure sufficient contact ratio. When intentional deviations are used, the scale readings show whether or not sufficient length of true involute is left on the teeth to insure their carrying the load from one tooth to the next.

Checking the tooth surfaces in the axial direction is done on fixtures like the one shown in Figure 15 if the gears are spur gears, and on helical lead machines per Figure 16 if the gears are helical. The tooth surface of a helical gear has the same lead at all diameters. Therefore, the lead check can be carried out at any radius between the root and outside diameters. (See Figure 14)

TABLE 6

INVOLUTE TOLERANCES FOR SPUR AND HELICAL GEARS

Class Pitch Diameter, In.	Diametral Pitch	*Profile Error Exclusive of Tip Modification								
		¾	1	3	6	12	25	50	100	200
Class 1 (Up to 80 fpm)	½	...	...	...	...	...	250	260	280	300
	1	...	...	...	...	50	60	70	80	90
	2	...	...	...	30	35	40	45	50	55
	4	...	...	25	30	35	40	40	40	45
	8	...	20	20	25	25	30	30	...	...
	16	15	15	15	20	20	25	...	...	...
Class 2 (Up to 400 fpm)	1	...	...	...	...	30	35	40	40	45
	2	...	...	...	20	20	25	30	30	35
	4	...	...	10	10	11	12	12	12	14
	8	...	9	9	9	9	9	10	...	...
	16	7	7	7	7	7	7	8	...	...
Class 3 (Up to 2000 fpm)	2	...	...	...	11	11	11	11	11	11
	4	...	...	8	8	8	8	8	8	8
	8	...	6	6	6	6	6	6	6	6
	16	5	5	5	5	5	5	5	...	...
Class 4 (Over 2000 fpm)	2	...	...	...	9	9	9	9	9	...
	4	...	...	...	5	5	5	5	5	5
	8	...	...	4	4	4	4	4	4	4
	16	...	3	3	3	3	3	3	3	3

**All tolerances in ten-thousandths of an inch.*

The accuracy of the straightness or lead is commonly related to tooth bearing and not to rotation. Some lead errors could be visualized which would affect the accuracy of the rotation in the way involute errors do, but the possibility is small and usually ignored.

The spacing of gear teeth can be—and sometimes is—checked by optical dividing heads and index plates. Such a check, however, is slow—too slow to be of practical use in the day in and day out control of gear quality.

Most gears are not indexing gears but are meant to transmit power. Since only one to two teeth are in engagement at a time, the manufacturers of gears are primarily interested in those variations in tooth spacing which affect the smoothness of their engagement rather than their total index errors. To be true, accumulated or maximum index errors are also important because they could not possibly happen without variations in tooth spacing. However, since these accumulations are a relatively stable function of the machine, they need checking only from time to time. Minimizing the accumulated errors by maintaining the machines helps to minimize space variations.

FIGURE 14

Helical Lead Charts of Mating Gears Superimposed.

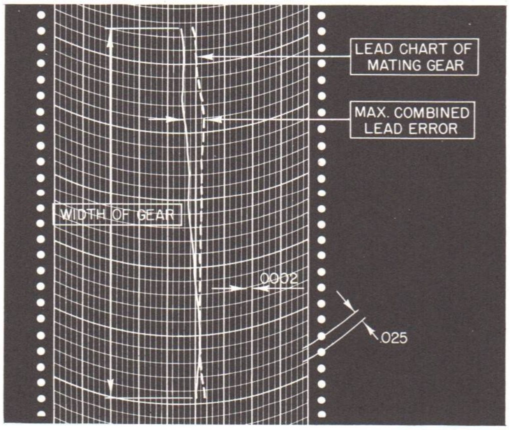


TABLE 7

AGMA TABLE OF LEAD ERRORS

Class Pitch Diameter, In.	*Circumferential Lead Error Per Width of Face			
	1″	6″	12″	18″
Class 1 (Up to 80 fpm)	13	50	..	..
	9	18	..	..
	8	16	..	..
	7	14	..	..
	7	13	..	..
	6	12	..	..
Class 2 (Up to 400 fpm)	6	11	..	..
	5	10	..	..
	5	9	..	..
	4	8	..	..
	4	8	..	..
Class 3 (Up to 2000 fpm)	4	8	..	..
	4	7	..	..
	3	6	..	..
	3	6	..	..
Class 4 (Over 2000 fpm)	4	7	11	..
	3	6	8	10
	2	4	6	8
	2	4	6	8

**All tolerances in ten-thousandths of an inch.*

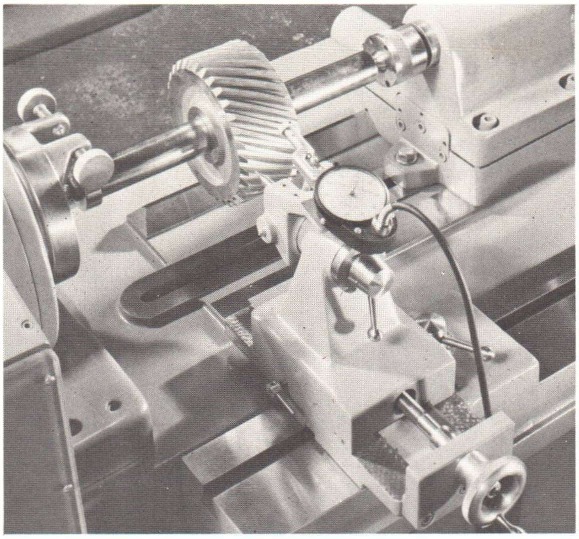


FIGURE 15

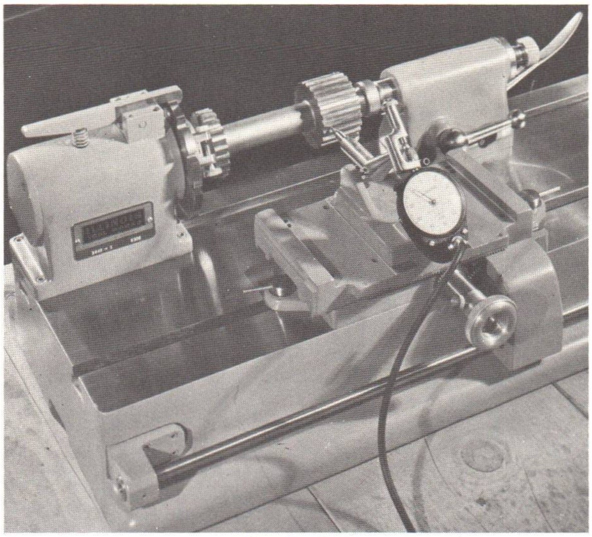


FIGURE 16

Most space "measuring" machines in the gear industry are "comparators". They compare the spacing of the teeth and measure only the variations. The AGMA suggests the following (Table 8) maximum variation.

As previously pointed out, the breakdown into four classes according to speed is, by necessity, arbitrary but intelligent interpretation can extend the usefulness of these suggested tolerances.

In the case of involute and space tolerances it is entirely permissible to consider them simultaneously because space variations *together* with involute variations, determine the smoothness of engagement of a pair of gears. Therefore, greater involute tolerances may be traded for tighter space tolerances, or vice versa. In a way, that sort of trading is automatically done in the selection of the basic cutting process: hobbing produces better spacing but poorer involutes, shaping has better involutes but relatively poorer spacing.

TABLE 8

AGMA TABLE FOR MAXIMUM VARIATION OF PITCH

Class	Diametral Pitch	*Maximum Index Error Between any Two Teeth Exclusive of Runout Effect									*Pitch Variation Measured on Pitch Circle in Plane of Rotation								
Pitch Diameter, In.		**¾**	**1**	**3**	**6**	**12**	**25**	**50**	**100**	**200**	**¾**	**1½**	**3**	**6**	**12**	**25**	**50**	**100**	**200**
Class 1 (Up to 80 fpm)	½	...	...	...	...	...	...	...	...	...	...	...	...	...	...	80	140	220	300
	1	...	...	...	...	...	...	...	...	...	...	...	...	...	50	75	125	180	250
	2	...	...	...	...	...	...	...	...	...	...	...	...	40	50	70	100	150	200
	4	...	...	...	...	...	...	...	...	...	...	...	30	40	50	60	90	120	150
	8	...	...	...	...	...	...	...	...	...	...	15	20	25	30	35	35	...	...
	16	...	...	...	...	...	...	...	...	...	15	17	20	25	25	...	...	...	...
Class 2 (Up to 400 fpm)	1	...	...	...	...	...	...	...	...	...	...	...	...	...	25	35	45	60	80
	2	...	...	...	...	...	...	...	...	...	...	...	...	10	15	20	25	30	50
	4	...	...	...	...	...	...	...	...	...	...	...	5	6	7	8	9	10	20
	8	...	...	...	...	...	...	...	...	...	...	5	5	6	6½	7	7	...	...
	16	...	...	...	...	...	...	...	...	...	3½	3½	4	4	4½	5	5½	...	...
Class 3 (Up to 2000 fpm)	2	...	...	...	20	20	27	43	70	100	...	...	...	5	5	5½	6	6	8
	4	...	...	15	15	15	21	33	53	75	...	...	3½	3½	4	4	5	5	7
	8	...	15	15	15	15	15	30	45	60	...	3½	3½	3½	4	4	5	5	6
	16	15	15	15	15	15	15	24	...	...	2½	2½	3	3	3½	3½	4	...	...
Class 4 (Over 2000 fpm)	2	...	...	...	10	10	12	20	30	...	...	...	...	4	5	5	5	5	...
	4	...	...	...	10	10	12	20	30	30	...	...	...	3½	4	4	4	4	4
	8	...	...	10	10	10	12	20	30	40	...	...	2½	2½	3	3	3	3	3
	16	...	10	10	10	10	12	20	30	...	...	2	2½	2½	2½	3	3	3	...

**All tolerances in ten-thousandths of an inch*

The space comparator shown in Figure 18 is a versatile, hand operated model. It is more versatile than the automatic checking machine shown in Figure 17, in the sense that the indicator head can also be adjusted to compare the normal pitch of helical gears and the base pitch of all gears.

Base pitch is the circular pitch at the base diameter. It is also the distance between successive driving involutes measured along a line running tangent to the base circle. All contact between two involute gears takes place on lines which run tangent to the base circle. Base pitch variations are theretore an indication of the smoothness of engagement because they are a combination of involute and spacing variations. The limitation of the base pitch check is that it can only be carried out over a limited area of the total active tooth surface. See Figure 19.

If an inspector wants to arrive at the accumulated error and its location on the gear, he has to process the measured variations as described on Page 7. However, he has another graphic method open to him which uses the measured variations directly.

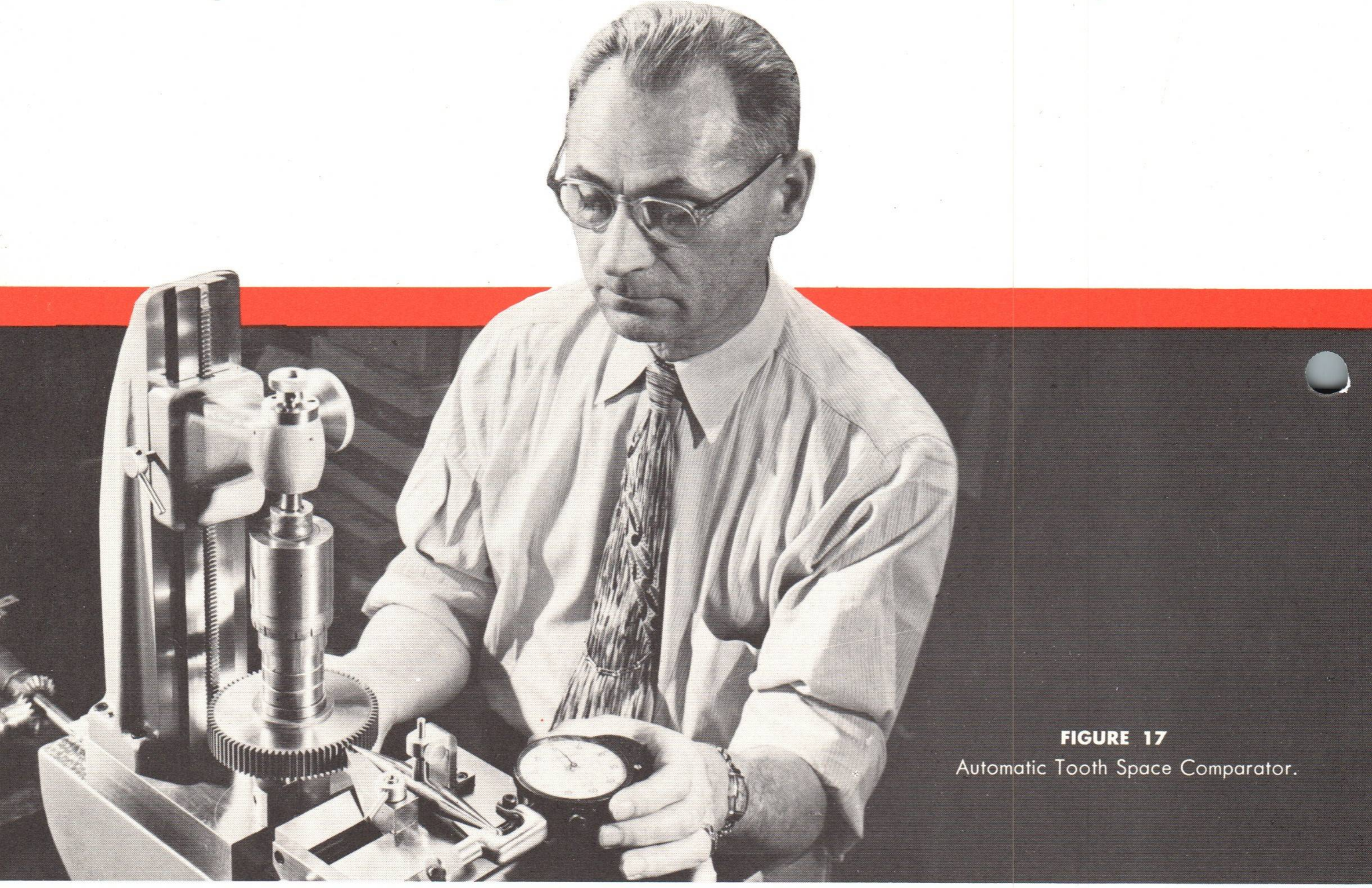


FIGURE 17
Automatic Tooth Space Comparator.

TABLE 9

Tooth Number		1	2	3	4	5	6
TT Indicator Reading		0	+.0002	+.0003	+.0004	+.0002	0
Algebraic Addition	0	0	+.0002	+.0005	+.0009	+.0011	+.0011
Tooth Number		**7**	**8**	**9**	**10**	**11**	**12**
TT Indicator Reading		0	+.0001	−.0002	−.0001	−.0002	−.0001
Algebraic Addition		+.0011	+.0012	+.0010	+.0009	+.0007	+.0006

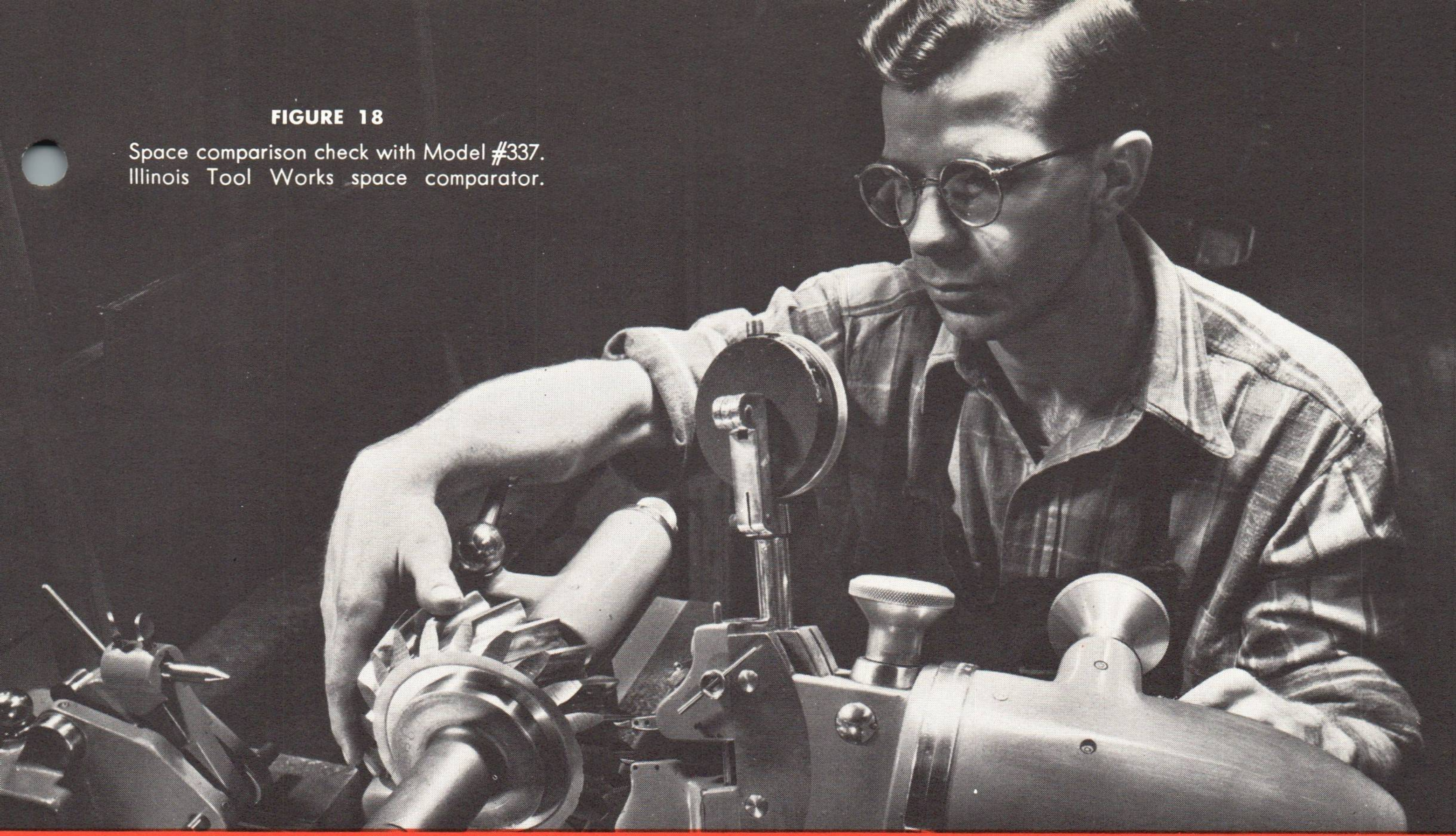


FIGURE 18

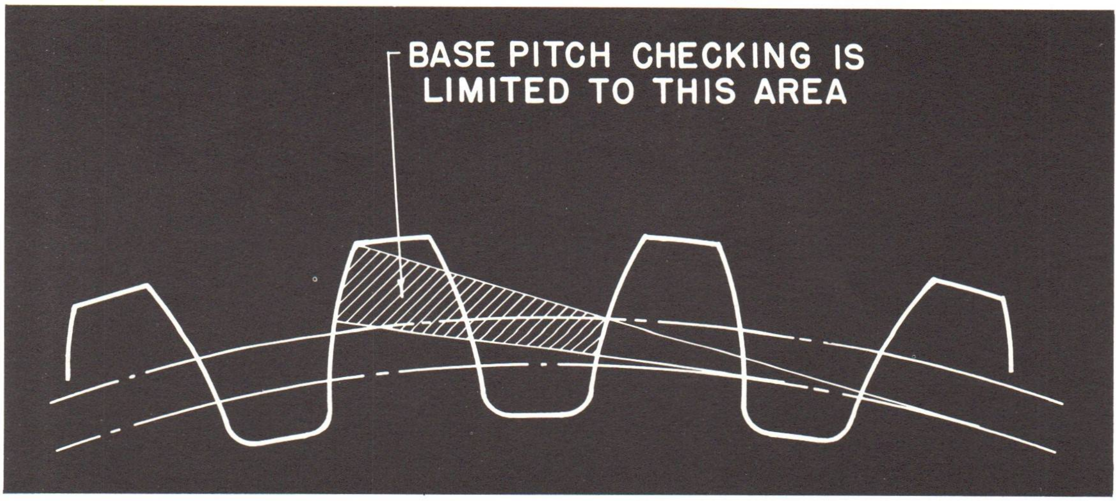
Space comparison check with Model #337. Illinois Tool Works space comparator.

He merely enters the figures in a graph consecutively adding or subtracting each space variation to or from the previous one. A line connecting the end point with the starting point represents all correct tooth positions. The out-of-position of all other teeth is then measured from this line. The maximum difference between any two points from this line is the accumulated error. See Figure 20.

Any hand operated space comparator is somewhat limited in its ultimate accuracy because the measured space variations are, as a rule, very small increments and easily subject to distortion unless great skill and patience are used. An automatic machine, as in Figure 17 does not suffer from the same handicap, particularly if it is combined with recording.

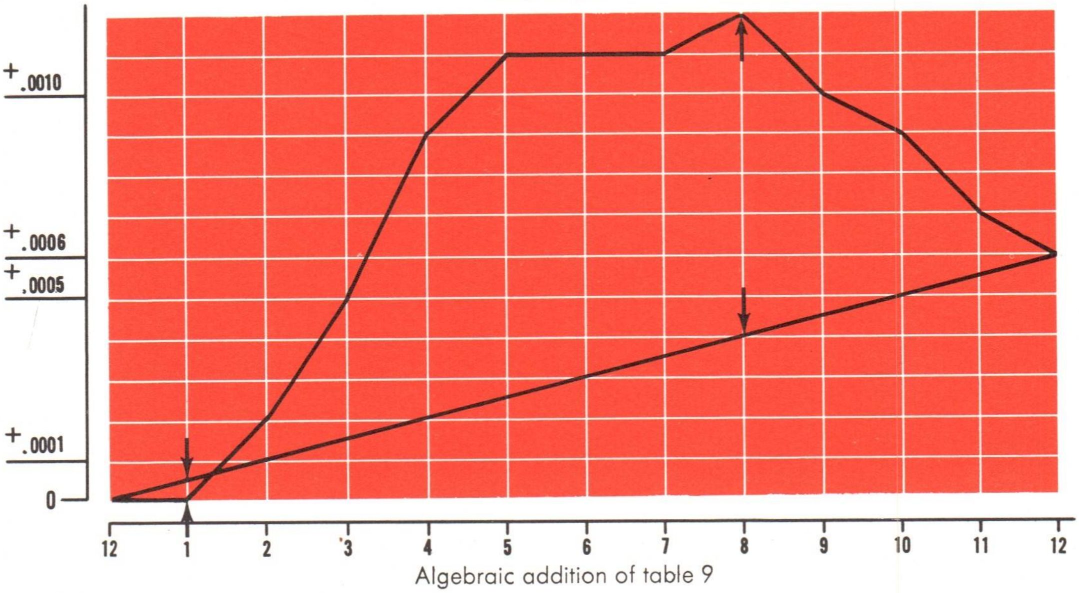
FIGURE 19

Limitations of base pitch checking



As previously mentioned, there are those in the gear industry who maintain that pitch variations should not be used to arrive at the accumulated error; that small misinterpretations of individual readings lead to large misinterpretations of the accumulated error. However, if these faulty dial indicator readings were consistently wrong in one direction or the other, they would not do any harm at all. If they are sometimes plus and sometimes minus, they will probably average out. The final proof to the argument lies in repetition; if several space checks of different gear diameters give uniform results, the checks are reliable and the accumulated error correct.

FIGURE 20



Summary

Gear inspection today means control over an increasingly complicated manufacturing cycle where hobbing depends on blanks, shaving upon hobbing and final accuracy upon heat treatment in addition to all other previous operations.

The problem is in finding the proper type and degree of inspection because gear inspection, correctly applied, reduces overall costs by:

- *Assuring a definite degree of uniformity in keeping with the specific service requirements.*
- *Permitting engineers to specify the most economical gear size and design.*
- *Reducing scrap and rejections.*

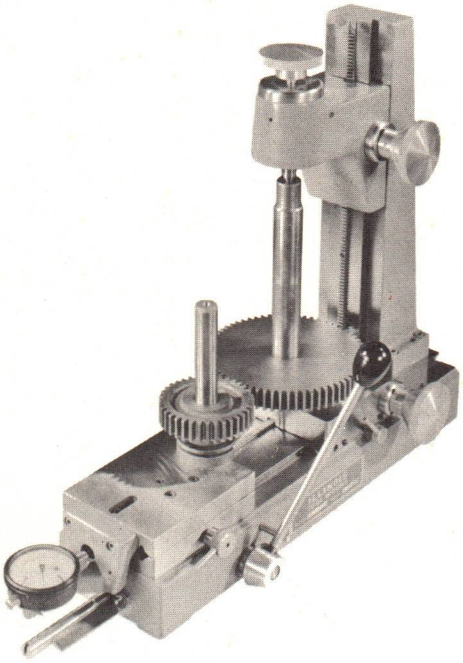
Inspection may be carried to the gear generating machines and it may be by functional and analytical checking.

By and large, the functional checking machines are the policemen of the gear manufacturing process; the analytical machines are the judges.

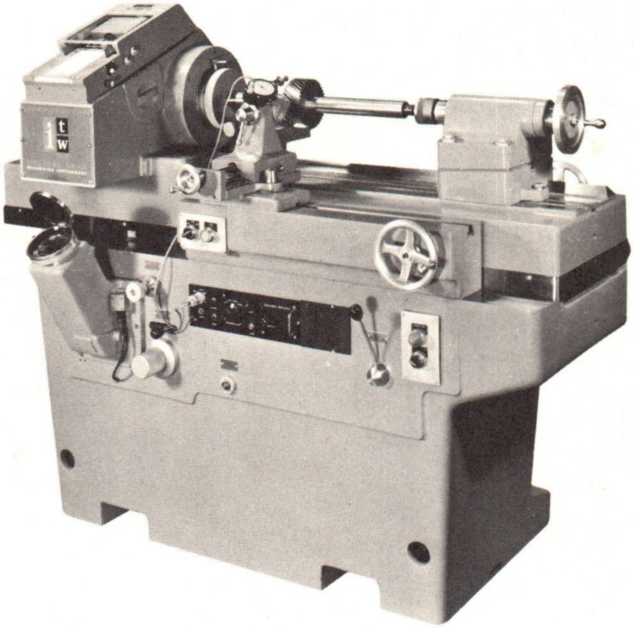
Any gear operation, large or small, is controlled most economically by the intelligent combination of these basic checking procedures and machines.

ILLINOIS TOOL WORKS MEASURING MACHINES

The machines shown here are but a part of the complete line of Illinois Tool Works Measuring instruments. Send for Measuring Machine Catalog AD-20 for complete product illustrations and descriptions.

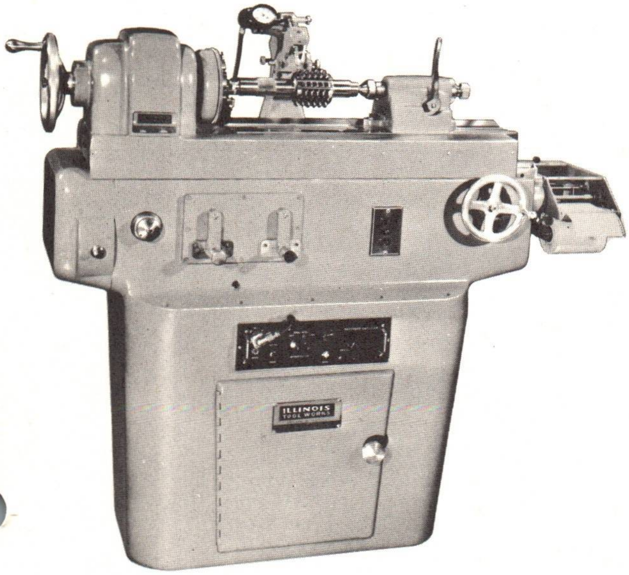


FUNCTIONAL GEAR MEASURING MACHINES



ANALYTICAL GEAR MEASURING MACHINES

HOB AND WORM MEASURING MACHINES



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